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A Causality Analysis on Economy-Energy-Climate of Developing Countries
: Focusing on the Effects of Climate-Related Development Finance

Lee, Minjoo* · Lim, Jae-Bin**

Abstract

The intensification of climate change has resulted in increased focus on the interconnectedness of various economic and social sectors in recent years. In particular, studies investigating the relationships between environment and various socio-economic factors have increased. These studies are similar to those pertaining to the environmental Kuznets curve (EKC) hypothesis, as well as 3E studies, which focus on the interconnections among economy, energy, and environment. This study aims to extend this 3E model by investigating the economic–energy–climate nexus in developing countries as well as the effects of climate cooperation and technological cooperation.

Hence, we constructed a simultaneous equation model to analyze the causality among economic growth (Gross Domestic Product per capita), energy (renewable-energy consumption), and climate change (carbon emissions) in 127 developing countries from 2005 to 2019. We employed the System GMM method of dynamic panel analysis for an efficient estimation. The results were categorized into economic, energy, and climate models. The economic model shows that renewable-energy consumption promotes economic growth, whereas carbon emissions hinder it. The energy model indicates that both economic growth and carbon emissions adversely affect renewable-energy consumption. In the climate model, the EKC hypothesis for economic growth is validated, where renewable-energy consumption is shown to reduce carbon emissions. Furthermore, the interaction terms indicate that climate cooperation and technological cooperation positively affect economic growth and renewable-energy consumption, whereas they adversely affect carbon emissions, thus demonstrating the synergistic effects of these cooperations.

Keywords Economy-Energy-Climate Nexus, Climate Cooperation, Technological Cooperation, Dynamic Panel Analysis, Sys GMM
주제어 경제-에너지-기후 넥서스, 기후협력, 기술협력, 동적패널분석, 시스템 GMM

Ⅰ. Introduction

Research on the nexus or the causal relationship between economic growth, renewable energy, and climate change recently has been actively conducted (Salari et al., 2021; Zhang et al., 2022). The Environmental Kuznets Curve (EKC), which is a representative theory for identifying the causality between the environment and economic growth, is still employed in many studies as part of the research on the environment-economy nexus, and has further expanded its scope to various fields such as food, health, and agriculture (Salari et al., 2021). This may be because the worsening of environmental problems such as climate change poses a major threat to the sustainable growth of countries, companies, and individuals and thus attempts are being made to identify their relationships

* Ph.D., Department of National Public Policy, Chungnam National University (First Author: lee.mj917@gmail.com)
** Professor, Graduate School of National Public Policy in Chungnam National University (Corresponding Author: jb.lim@cnu.ac.kr)

with socioeconomic variables.

Climate change is organically linked to energy consumption as well as the economy. The international community is actively seeking solutions to ensure energy sustainability and reduce greenhouse gas emissions as environmental pollution and climate change are accelerated (Zhang et al., 2022). Among the possible solutions, renewable energy is drawing attention as a key element of the carbon neutral strategy that can promote the structural transformation of energy, protect the Earth's ecosystem, and alleviate the climate crisis.

Meanwhile, the dynamics among energy consumption, economic growth, technological development, and trade openness have been continuously discussed; in addition, the role of renewable energy as an alternative energy source to fossil fuels has been emphasized, and research on its impact on economic growth has also increased (Akizu-Gardoki et al., 2018; Alam and Murad, 2020). Traditionally, renewable energy has been recognized as having a negative impact on economic growth by increasing energy costs. However, recently, with technological advancements, the cost of renewable energy is approaching the level of fossil energy, and there is a growing opinion that the renewable energy industry and serve as a new economic growth engine (Kim, 2021).

Response to climate change is a common task for both developed and developing countries, but the extent of damage and loss resulting therefrom is somewhat unbalanced. Since most developing countries have lower economic and social response capacities than developed countries, their capacity to reduce greenhouse gas emissions, the essential cause of climate change, or to adapt to climate change is likely to be limited. Above all, countries that have not yet achieved economic and social growth have no choice but to prioritize 'development' over environmental or climate change issues. In particular, the logic that the so-called large emerging countries (BRICs),[1] such as China, Russia, and India, promote is intertwined with the need, and at the center of the logic is the fact that the countries that have caused the current climate crisis have achieved rapid development based on fossil fuels. This is the essential conflicting factor between developed and developing countries at the UNFCCC Conference of the Parties (COP). Therefore, in order to narrow the differences of opinion, it is necessary to closely analyze the economy-energy-climate nexus that is suitable for the situation of developing countries.

The purpose of this study is to empirically verify the economy-energy-climate nexus, that is, the reciprocal causal relationship, focusing on developing countries that are the target of international development cooperation. In particular, this study aims to introduce climate-related development finance and technology cooperation finance to the economy-energy-climate nexus of developing countries in order to identify the impact of climate and technology finance on developing countries. To this end, we established a simultaneous equations model that considers the economy-energy-climate interconnections, and then estimated each simultaneous equation using the System Generalized Moment Method (System GMM), a dynamic panel model capable of producing efficient results by eliminating endogeneity between variables using instrumental variables. We expect that the present study will contribute to effectively setting the fiscal policy direction for 'climate cooperation and technology cooperation'[2] for developing countries.

Ⅱ. Previous Studies and Distinctiveness of Present Study

1. Economy-energy-climate nexus

Economy, energy, and climate have a complicated nexus (Zhang et al., 2022). This can support the argument that climate change is a result of human activities, as industrialization and development to promote economic growth have contributed to increased fossil fuel consumption (Salari et al., 2021). Since the early 1990s, when the international community began to discuss climate issues in earnest, the need to reduce greenhouse gas emissions centered on carbon dioxide has become a major issue, along with the utilization of renewable energy, which is eco-friendly, clean, and non-depletable. Since renewable energy is a type of technological energy, developed countries are leading its development and production, and as large-scale research and development and investment are required, it has now been industrialized and marketed, becoming another factor in the national economy.

Due to the unique relationship among economy, energy, and climate, various macroeconomic studies are being conducted. Conventionally, the relationship is constructed into the 3E (energy-environment-economy) model. However, the EU, the region most active in environmental issues, has developed the E3ME (energy-environment-economy global macro-economic) model, which is currently used for policy evaluation and economic forecasting for 61 countries including the EU. The overview of E3ME shown in 〈Figure 1〉 indicates that economy-emissions-energy affect each other bilaterally. Factors such as economic activity and prices cause changes in the amount of energy consumption, and increased energy consumption increases greenhouse gas emissions, which in turn affects the economy and economic activity in the form of carbon emission trading systems and environmental taxes.

2. Climate cooperation and technology cooperation and economy-energy-climate nexus

With worsening climate change, humankind is faced with the difficult task of implementing climate action and development simultaneously. Countries that have achieved a certain level of economic growth are exerting efforts to achieve sustainable development, while developing countries that prioritize economic growth over environmental issues are in a situation where it is difficult to accelerate development in the global climate cooperation trend. Developed countries that are responsible for causing climate change historically are responsible for not only reducing greenhouse gases but also providing financial and technological support to enable developing countries to cope with climate change and continue to grow. Accordingly, these nations are striving to strengthen the linkage between financial and technological mechanisms to accelerate climate action in developing countries (UNFCCC, 2016; Bose, 2019).

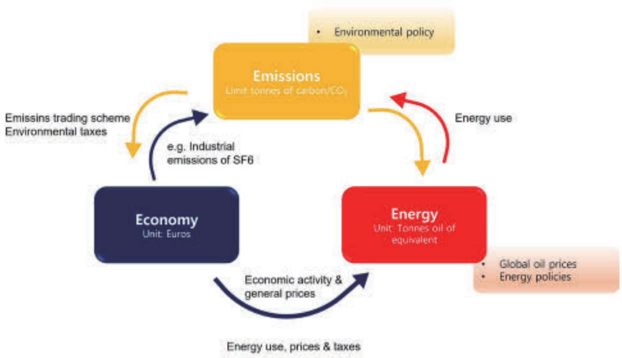

Figure 1. E3ME model for EU

Source: I2Am PARIS

In 2009, developed countries pledged climate finance of 100 billion dollars annually until 2020 to support climate action in developing countries. But due to their continued failure, the target period was extended to 2025 in the 2015 Paris Agreement, and the amount exceeded 100 billion dollars for the first time in 2022 (OECD, 2024). The international community is mobilizing various financial resources to supplement the insufficient climate finance, such as starting to establish a new climate finance target at COP26 in 2021. This suggests that climate finance through climate cooperation plays an important role in climate change mitigation and adaptation and socio-economic development in developing countries. Lee et al. (2022) investigated the impact of climate finance on carbon emissions in 133 developing countries between 2000 and 2018 and found that it contributed to reducing carbon emissions. This confirmed that the effect of climate change mitigation finance was more prominent than that of adaptation finance. Briera and Lefèvre (2024) employed IMACLIM-R (Multi-Regional Integrated Assessment Model) to conduct a macroeconometric analysis of the impact of climate finance on renewable energy transition in developing countries. The results showed that although the high capital costs serve as an obstacle to renewable energy transition, climate finance reduces the capital costs, thereby helping accelerate the renewable energy transition. In a similar vein, Njangang et al. (2024) attempted to assess the impact of climate finance on energy vulnerability in developing countries using the GMM model. The analytical results showed that climate finance has a positive impact on reducing energy vulnerability in developing countries, but the results were significant only in countries with high energy vulnerability.

Along with climate finance, the importance of technological cooperation has been continuously emphasized in reducing greenhouse gas emissions and responding and adapting to the impacts of climate change (UNDP, 2011). Technology development and transfer to support national actions on climate change have been recognized as essential elements since the early stage of the establishment of the UNFCCC, and specific technology-related provisions were stipulated in the 1992 Convention (UNFCCC, 2016).[3)] In this context, it is necessary to focus on research on the impact of technological cooperation, and Mallett (2012) argued that technological cooperation could enhance the sustainability of the energy sector. Pandey et al. (2022) predicted that innovative cooperation, including technological cooperation, would lead to sustainable development in the energy and environment sectors of developing countries, effectively achieving economic development goals. In addition, technological cooperation related to renewable energy as a technological energy is expected to play a major role in the environment and energy sectors of developing countries. Usman and Balsalobre-Lorente (2022) argued that investment in clean energy such as renewable energy would reduce the ecological footprint of the top 10 countries that achieved industrialization between 1990 and 2019 and reduce the negative impacts of climate change.

There are also studies that do not limit the scope of analysis to developing countries, in which cases climate finance can be applied in financial forms such as green bonds and environmental taxes, and technology finance as technological innovation. Mensah et al. (2019) conducted a study using STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) and IPAT (Impact = Population × Affluence × Technology) models on the impact of technological innovation and environmental budgets and taxes on the economy and green growth between 2000 and 2014 in 28 OECD member countries, and the results showed that the relationship between technological innovation and green growth differed by region, and environmental budgets and taxes contributed to green growth in all regions. Zhang et al. (2022) performed a dynamic panel analysis on the impact of green bonds and technological innovation on the energy-environment-climate change by selecting countries from different regions. Regarding the moderating effect of green finance and technological innovation, the results showed that technological innovation has a positive effect on renewable energy consumption, which is strengthened by green finance, whereas when the level of green finance is high, technological innovation has the effect of reducing carbon emissions, thereby weakening the impact on climate change. In other words, it was confirmed that green finance moderates the relationship between innovation and energy-environment-climate change.

3. Distinctiveness of present study

As can be seen in previous studies, the scope of research on economy-energy-climate is expanding based on various endogenous and exogenous factors, while the results may differ to some extent depending on the analysis target and analysis period. When 3E model estimation is carried out based on the dynamic stochastic general equilibrium (DSGE) model, which has been the mainstream macroeconomic model since the 1980s, there are limitations in that the analytical results are highly sensitive to the selection of parameters and the analysis of multiple macroeconomic time-series of a country is difficult (Baek and Hwang, 2009). Therefore, the aim of the present study is to discuss the economy-energy-climate nexus in developing countries by establishing a simultaneous equations model (SEM) system, which is widely used as a macroeconomic model.

Meanwhile, since climate change-related finance and technology are being packaged and intensively discussed as climate strategies, many countries are also making efforts to develop climate finance and climate technology (Li et al., 2018). Steadily increasing studies have been performed by using various terms such as green finance, climate finance, green financial resources, climate financial resources, climate technology, green technology, and technological innovation, but research dedicated to analyzing the influence on the 3E model of the simultaneous equations system is limited. In the case of developing countries, the government capacity is limited due to their economic, political, and social vulnerability, and thus there may be some limitations in identifying the impact of climate and technology-related factors utilized in previous studies. For this reason, the present study differs from previous studies in that the economy-energy-climate interrelationships of developing countries are examined together with moderating effects of climate cooperation and technological cooperation (Figure 2).

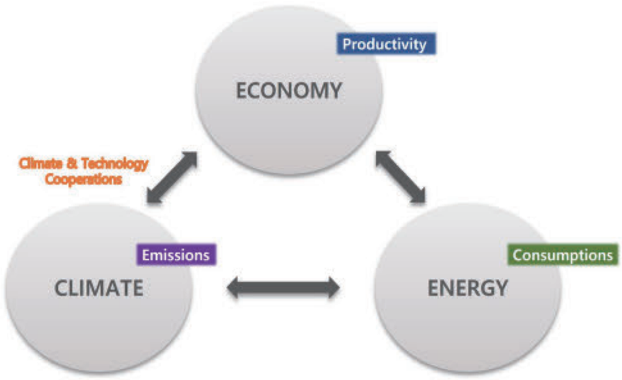

Figure 2. Theoretical framework

III. Study Design and Analysis

1. Analytical method

In the present study, we focused on understanding the organic economy-energy-climate relationship in developing countries. Here, climate, economy, and energy may be considered as endogenous variables that are determined simultaneously. Due to the simultaneity or endogeneity between variables, when estimated with a simple regression analysis (ordinary least squares, OLS), even when the error term (ϵ_{it}) is removed, the correlation between the explanatory variables and the error term remains, which causes bias in the estimation. In order to obtain a consistent estimator, the equation can be estimated using appropriate instrumental variables, and exogenous variables of other equations are input as instrumental variables. The complicated economy-energy-climate relationships also cause endogeneity problems, and thus it is necessary to estimate the connectivity over time (Zhang et al., 2022). Therefore, in order to solve the unavoidable endogeneity problem, we considered a dynamic panel model capable of deriving efficient estimates when lagged variables are used as explanatory variables. The dynamic panel model includes lagged variables of the dependent variable in the explanatory variables, and the basic formula is as follows.

$$y_{it} = \alpha + \gamma y_{it-1} + \beta x_{it} + u_i + \epsilon_{it} \quad (1)$$

In Equation (1), y_{it-1}, an endogenous explanatory variable, can be estimated using instrumental variables after being first differenced to alleviate endogeneity. However, the characteristic of the panel group unobserved through difference transformation, u_i, is removed from the model represented by Equation (2), but the explanatory variables Δy_{it-1} and the error term are still correlated because $cov(y_{it-1}, \epsilon_{it-1}) \neq 0$.

$$\Delta y_{it} = \gamma \Delta y_{it-1} + \beta \Delta x_{it} + \Delta \epsilon_{it} \quad (2)$$

$$cov(\Delta y_{it-1}, \ \Delta \epsilon_{it}) = cov(y_{it-1} - y_{it-2}, \ \epsilon_{it} - \epsilon_{it-1}) \neq 0 \quad (3)$$

Therefore, the first difference Equation (2) still requires an instrumental variable estimation method, where Arellano and Bond (1991) derived the GMM estimator using lagged variables ($y_{it-2}, y_{it-3}, \cdots$) of y_{it-1} as instrumental variables for Δy_{it-1} (Min and Choi, 2019). Here, the instrumental variables ($y_{it-2}, y_{it-3}, \cdots$) must satisfy two conditions, as shown in Equation (3): first, they must be correlated with the endogenous explanatory variables (Δy_{it-1}), and second, they must not be correlated with the error term ($\Delta \epsilon_{it}$).

Meanwhile, panel GMM estimation is an analysis method suitable for cases where the number of instrumental variables is greater than the number of endogenous explanatory variables, that is, over-identified models, and is divided into a difference GMM and a system GMM. While the difference GMM has a problem of finite sample bias, the system GMM, which is created by combining the level equation and difference equation into one system by imposing an additional moment condition[4] between instrumental variables and error terms, enables derivation of an estimator that is more efficient than the difference GMM (Arellano and Bover, 1995; Blundell and Bond, 1998). In other words, the system GMM selects Δy_{it-1} as instrumental variables of y_{it-1} in Equation (1), and since y_{it-1} is correlated with the error term u_i, it becomes an endogenous explanatory variable. Therefore, the instrumental variable Δy_{it-1} enables verification of the correlation between endogenous explanatory variables y_{it-1} ($cov(\Delta y_{it-1}, \ y_{it-1}) \neq 0$). Next, there must be no correlation between the error term and the instrumental variable ($cov(\Delta y_{it-1}, \ u_i) = 0$). At that time, Δy_{it-1} is the difference between y_{it-1} and y_{it-2}, each of which includes u_i. Thus, u_i is removed when they are differenced, and the correlation between Δy_{it-1} and u_i is eliminated. Therefore, in the present study, we used the system GMM method with improved efficiency of the difference GMM estimators.

In the system GMM, the additional moment condition is $E[\Delta y_{it-1}(u_i + e_{it})] = 0$, where $u_i + e_{it}$ is an error term of the level equation represented by Equation (1). The system GMM estimators are obtained by minimizing the objective function that is formed by making the moment condition of the level equation and the difference equation into a system of equations, as shown in Equation (4). Here, Z_{1it} is the instrumental variable vector of the difference equation, Z_{2it} is the vector of the level equation, and the weight matrix W is constructed in consideration of the first-order autocorrelation problem in the difference equation (Min and Choi, 2019).

$$Q(\alpha,\gamma,\beta)=\begin{bmatrix}\frac{1}{nT}\sum_{i=1}^{n}\sum_{t=1}^{T}Z_{1it}\Delta e_{it}\\ \frac{1}{nT}\sum_{i=1}^{n}\sum_{t=1}^{T}Z_{2it}e_{it}\end{bmatrix}' W\begin{bmatrix}\frac{1}{nT}\sum_{i=1}^{n}\sum_{t=1}^{T}Z_{1it}\Delta e_{it}\\ \frac{1}{nT}\sum_{i=1}^{n}\sum_{t=1}^{T}Z_{2it}e_{it}\end{bmatrix} \quad (4)$$

2. Variables and research model setup

The main object of the present study is to expand the existing 3E model to identify the mutual relationships among economy (economic growth), energy (renewable energy consumption), and climate (carbon emissions) and analyze the impact of climate finance and technology finance, provided by developed countries to developing countries, on the economy-energy-climate nexus. The analytical targets were 127 developing countries, and we used the data from the World Development Indicators (WDI) of the World Bank, the Organization for Economic Cooperation and Development (OECD), and the International Energy Agency (IEA), as published on their websites.

The analysis period was set from 2005 to 2019, considering the data availability for key variables, and panel data was constructed. First, since the Rio Marker was officially introduced in 2002, the year 2005, which was some time later from 2002, was selected as the starting point to acquire more stable data. The reason for excluding the data from 2020 is because abnormal volatility was observed in some data such as GDP per capita, due to the COVID-19 pandemic, and data thereafter are not fully provided.

The dependent variables were set as per capita GDP (ln*GDPP*), renewable energy consumption rate (*REC*), and per capita carbon emissions (*CO2*), and the explanatory variables were climate cooperation finance (ln*CF*) and technology cooperation grant (ln*TEC*), and the cross-term of climate cooperation finance and technology cooperation grants (ln*CF*×ln*TEC*) was added to confirm the moderating effect. In order to focus on identifying the influence of these factors, gross fixed capital formation (*GFCF*), labor force (ln*LA*), trade openness (*TO*), proportion of primary energy consumption (ln*EC*), proportion of industrialization (*INDUS*) and urbanization (*URBAN*), proportion of foreign direct investment (FDI) (*FDI*), inflation rate (*INFLAG*), and total population (ln*POP*) were analyzed. The operational definitions of the above-mentioned variables are shown in 〈Table 1〉.

Table 1. Variables description

Variable		Description	Unit	Source
Dependent	lnGDPP	Natural logarithm of GDP per capita in constant 2015	USD	WDI
	REC	Renewable energy consumption of total final energy consumption	%	IEA
	CO2	CO_2 emissions per capita	metric ton	WDI
Independent	lnCF	Natural logarithm of climate-related development finance (ODA+OOF+private)	USD	OECD
	lnTEC	Natural logarithm of technical cooperation grants (BoP)	USD	OECD
Control	GFCF	Gross fixed capital formation as a share of GDP	%	WDI
	lnLA	Natural logarithms of labour force	person	WDI
	TO	Trade openness, Imports of goods and services as a share of GDP	%	WDI
	lnEC	Natural logarithm of primary energy consumption per capita	kg	IEA
	INDUS	Industry value added as a share of GDP	%	WDI
	URBAN	Share of the population living in urban areas	%	WDI
	FDI	Foreign direct investment, net inflows as a share of GDP	%	WDI
	INFLAG	Inflation, measured using the GDP deflator	%	WDI
	lnPOP	Natural logarithm of total population	person	WDI

As a statistical model, we employed a simultaneous equations system in which the dependent variable of one estimation equation is given as the explanatory variable of the other two estimation equations. In particular, in the case of economic equations, we constructed an extended production function, which is commonly used in the 3E model, taking into account the fact that energy consumption is regarded as a production factor within the 3E nexus based on the Cobb-Douglas production function, as represented by Equation (5).

$$Y = f(A(K,E),L) \tag{5}$$

Here, Y refers to GDP, A represents factors of production, K is capital stock, L is labor force, and E is energy consumption. The combination of capital and energy consumption determines factors of production, and labor force is input to produce goods (Berndt and Wood, 1975; Stern, 1993). In addition, in the growth model introduced by Ayres and Nair (1984), energy is considered the only growth factor because a considerable energy source is required in the production process. Thus, capital and labor force serve as parameters, and energy is required to operate them. Applying this logic, Abdollahi (2020) created a production function including labor force, capital, and energy, and the applied equation is as follows.

$$Y = f(K,L,REC) \tag{6}$$

In addition, we constructed a climate equation based on the Environmental Kuznets Curve (EKC) theory, the basic formula for which is shown below.

$$Y = f(G,G^2,V) \tag{7}$$

Here, Y represents carbon emissions, G denotes income, and V represents other exogenous variables that may affect environmental quality, where the renewable energy consumption variable is added by applying the study by Dong et al. (2018):

$$Y = f(G,G^2,REC,V) \tag{8}$$

Accordingly, the basic economic-energy-climate simultaneous equations model to be utilized in this study is as follows.

[Economy equation] (9)

$$Economy_{it} = \beta_0 + \beta_1 Climate_{it} + \beta_2 Energy_{it} + \beta_3 Controls_{it} + \epsilon_{1it}$$

[Energy equation] (10)

$$Energy_{it} = \gamma_0 + \gamma_1 Climate_{it} + \gamma_2 Economy_{it} + \gamma_3 Controls_{it} + \epsilon_{2it}$$

[Climate equation] (11)

$$Climate_{it} = \alpha_0 + \alpha_1 Economy_{it} + \alpha_2 Energy_{it} + \alpha_3 Controls_{it} + \epsilon_{3it}$$

The GDP per capita (constant 2015), the proportion of renewable energy in total final energy consumption (%), and the carbon emissions per capita (metric tons) were input as the economy, energy, and climate variables, respectively, and the GDP per capita was transformed to a natural logarithm considering the balance with the entire data before use. Based on the above equations, we constructed a three-dimensional simultaneous equations framework including climate cooperation and technological cooperation as main variables in order to improve the model in accordance with the purpose of the present study. In addition, we added the interaction variables of climate cooperation and technological cooperation to examine the moderating effect more specifically, thereby exploring the essential roles of climate cooperation and technological cooperation in the economy-energy-climate nexus of developing countries. For climate cooperation, climate finance (constant 2015) including the Official Development Assistance (ODA) and bilateral and multilateral public and private climate-related finance were input by taking the natural logarithm, and data provided by OECD/Common Reporting Standard (CRS) through Rio Markers were utilized. For technical cooperation, data on technical cooperation grants (based on BoP) such as ODA, public and private finance, and Other Official Finance (OOF) were also utilized by taking the natural logarithm, and the data source is the same as for climate cooperation.

To avoid bias of omitted variables and control for country specificity and to investigate the influence of key variables more closely, we added various control variables (trade openness, primary energy consumption, urbanization, industrialization, FDI, gross fixed capital formation, labor force, inflation, development cooperation finance, etc.)

based on previous studies on economy, energy, and climate (environment). First, trade openness may contribute to economic and industrial growth and income increase in developing countries and help increase demand for climate-related technologies. However, there is also a possibility that some industries under lax climate and environmental regulations may enter the country, negatively affecting climate change and the environment (Antweiler et al., 2001; Copeland and Taylor, 2005; Feridun et al., 2006).

'Primary energy' in primary energy consumption refers to energy sources supplied from nature without being processed or modified, including crude oil, coal, natural gas, nuclear power, wood, and renewable energy. Excluding biomass and wood, fossil fuels account for more than 85% of primary energy demand, so and thus the correlation with industrialization and economic growth may be considered, while renewable energy can significantly reduce the use of the remaining types of primary energy (Soava et al., 2018; Abdollahi, 2020; Kandpal and Singh, 2022).

Industrialization and urbanization are typical factors that are pointed out as causes and results of economic growth, carbon emissions, and energy consumption, but they were added as control variables because they may show conflicting results depending on the socioeconomic and geopolitical conditions of the analytical subjects (Donglan et al., 2010; Poumanyvong and Kaneko, 2010; Shahbaz and Lean, 2012; Abdollahi, 2020; Zhang et al., 2022).

FDI can greatly contribute to the overall improvement of the economic level of developing countries (host countries), through, for example, technological diffusion and improvement of human capital capabilities. However, it also has the possibility of turning developing countries into 'pollution havens' as industries outside of the regulatory sphere enter the countries, relaxing the climate and environmental regulations (Sadorsky, 2010; Lee, 2013). Previous studies tended to focus on the economic effects of FDI, but with exacerbation of the climate crisis, research on its environmental effects has recently increased. In addition, studies are being conducted on its impact on energy consumption and carbon emissions as well as on its correlations with clean energy such as renewable energy (Mielnik and Goldemberg, 2002; Lee, 2013; Marton and Hagert, 2017).

Gross fixed capital formation and labor force are variables corresponding to capital (K) and labor force (L) in the above-mentioned production function, and they are the two basic factors of production and have the closest relationship with economic growth (Menyah and Wolde-Rufael, 2010; Abollahi, 2020; Rezitis and Ahammad, 2015). The results from previous studies vary to some degree depending on the variables that were input together or the analysis subjects, but the two factors are generally reported to be effective for economic growth.

The descriptive statistics for the above-mentioned variables are shown in 〈Table 2〉. Based on the selected vari-

Table 2. Descriptive statistics

Variable	Obs	Mean	Std. dev.	Min	Max
lnGDPP	1,905	7.6008	1.5587	0.0010	9.6654
REC	1,905	39.9189	31.2483	0.0000	97.4200
CO2	1,905	2.0424	2.4446	0.0000	15.3413
lnCF	1,905	16.5436	4.2736	0.0010	23.1078
lnTEC	1,894	17.7948	1.2217	13.1422	20.7838
GFCF	1,905	19.3627	11.7524	0.0000	78.0009
lnLA	1,785	15.1110	1.6987	10.4985	20.0699
TO	1,905	67.0148	41.7164	0.0000	347.9965
lnEC	1,890	8.3741	1.6819	0.0100	10.9996
INDUS	1,905	25.5636	13.2331	0.0000	86.6696
URBAN	1,905	44.4267	20.2977	0.0000	100.0000
FDI	1,905	4.1955	6.1882	-37.1727	103.3374
INFLAG	1,905	7.3941	12.3367	-30.1997	225.3946
lnPOP	1,905	15.7552	2.0575	9.2015	21.0476

ables, we improved the basic economic-energy-climate simultaneous equations model, represented by Equations (9) to (11), to construct the final research model.

[Economy equation] (12)

$$\begin{aligned} \ln GDPP_{it} = {} & \alpha_0 + \alpha_1 REC_{it} + \alpha_2 CO2_{it} + \alpha_3 \ln CF_{it} + \alpha_4 \ln TEC_{it} \\ & + \alpha_5 \ln CF^{*} \ln TEC_{it} + \alpha_6 GFCF_{it} + \alpha_7 \ln LA_{it} + \alpha_8 TO_{it} \\ & + \alpha_9 INDUS_{it} + \alpha_{10} URBAN_{it} + \alpha_{11} FDI_{it} + \alpha_{12} INFLAG_{it} \\ & + \epsilon_{1it} \end{aligned} \tag{12}$$

[Energy equation] (13)

$$\begin{aligned} REC_{it} = {} & \beta_0 + \beta_1 \ln GDPP_{it} + \beta_2 CO2_{it} + \beta_3 \ln CF_{it} + \beta_4 \ln TEC_{it} \\ & + \beta_5 \ln CF^{*} \ln TEC_{it} + \beta_6 GFCF_{it} + \beta_7 TO_{it} + \beta_8 \ln EC_{it} \\ & + \beta_9 INDUS_{it} + \beta_{10} URBAN_{it} + \beta_{11} FDI_{it} + \beta_{12} \ln POP_{it} + \epsilon_{2it} \end{aligned} \tag{13}$$

[Climate equation] (14)

$$\begin{aligned} CO2_{it} = {} & \gamma_0 + \gamma_1 \ln GDPP_{it} + \gamma_2 \ln GDPP_{it}^2 + \gamma_3 REC_{it} + \gamma_4 \ln CF_{it} \\ & + \gamma_5 \ln TEC_{it} + \gamma_6 \ln CF^{*} \ln TEC_{it} + \gamma_7 GFCF_{it} + \gamma_8 TO_{it} \\ & + \gamma_9 \ln EC_{it} + \gamma_{10} INDUS_{it} + \gamma_{11} URBAN_{it} + \gamma_{12} FDI_{it} + \epsilon_{3it} \end{aligned} \tag{14}$$

3. Test of analytical model and instrumental variable adequacy

The key to system GMM estimation is instrumental variables, and hence it is necessary to test the adequacy of instrumental variables to improve the reliability of the estimator. Therefore, we conducted a two-step test to confirm the adequacy of the instrumental variables. The first step is a test for over-identifying restrictions, which verifies whether the instrumental variables satisfy the moment condition with the error term. In a dynamic panel analysis, the number of instrumental variables is greater than the number of endogenous variables, which leads to over-identifying estimation, and thus it is necessary to test the adequacy. Two types of tests may be performed to test over-identifying restrictions: the Sargan test and the Hansen-J test. The Sargan test is valid only when the error term satisfies independence, normality, and homoscedasticity (Independently and Identically Distributed, I.I.D.), while the Hansen-J test can be used even when the error term has heteroscedasticity. For a more precise test in this study, we conducted the Hansen-J test that considers heteroscedasticity. The null hypothesis (H_0) for the above over-identifying restriction test is that 'all adopted instrumental variables are not correlated with the error term,' and when this null hypothesis is rejected, the over-identified model is determined to be inadequate (Min I.S. and Choi P.S, 2019). Second, it is necessary to test whether there is no serial correlation of the difference error term ($\Delta\epsilon_{it}$). When there is no autocorrelation in the error term, it is determined that the explanatory variables of all time lags can be used as instrumental variables. From Equation (3) described above, it can be seen that the difference error term has a first-order autocorrelation. In this case, when there is a second-order autocorrelation, $cov(y_{it-2},\ \Delta\epsilon_{it}) \neq 0$, and therefore the reliability of the adequacy of the instrumental variable arises. When selecting an adequate instrumental variable, it is assumed that there is no second-order autocorrelation for the difference error term, and thus it is necessary to test whether there is a first-order autocorrelation or a second-order autocorrelation. The Arellano-Bond test is an applicable test method, and when the instrumental variable is adequate, the test result should be that there is a first-order autocorrelation (rejection of the AR(1) null hypothesis) and there should be no second-order autocorrelation (adoption of the AR(2) null hypothesis).

We confirmed the adequacy of the instrumental variables in two steps by performing the Hansen-J test and the Arellano-Bond test. As a result, the null hypothesis was adopted for all of economy, energy, and climate in the Hansen-J test, and in the Arellano-Bond test, the AR(1) null hypothesis was rejected, and the AR(2) null hypothesis was not rejected.[5] In other words, the variables adopted in the present study were determined to be adequate as instrumental variables, and thus the economy-energy-climate model was finally estimated using the system GMM method. 〈Figure 3〉 shows a flowchart of the above-described analysis.

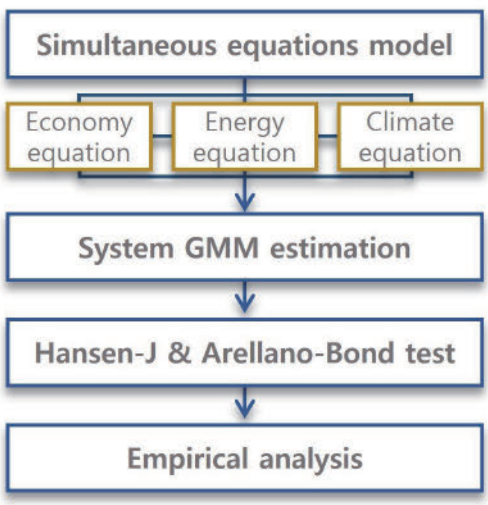

Figure 3. Methodological framework

Ⅳ. Analytical Results

1. Results of estimation of economic equations

The results of the estimation for the economic model showed that renewable energy consumption has a positive (+) effect on economic growth in developing countries, while carbon emissions have a negative (-) effect (Table 3). Although there is an argument that renewable energy consumption and economic growth show a dynamic rela-

Table 3. Results of the economy models

DV: lnGDPP	Model (1) [Basic]	Model (2) [lnCF]	Model (3) [lnTEC]	Model (4) [lnCF×lnTEC]	Model (5) [ALL]
L.lnGDPP	0.623*** (0.000315)	0.625*** (0.000496)	0.684*** (0.000607)	0.685*** (0.000636)	0.685*** (0.000635)
REC	0.00126*** (4.32E-05)	0.000993*** (5.14E-05)	0.000609*** (5.04E-05)	0.000569*** (5.15E-05)	0.000514*** (5.24E-05)
CO2	-0.0604*** (0.0012)	-0.0538*** (0.00132)	-0.0238*** (0.00185)	-0.0175*** (0.00191)	-0.0177*** (0.00181)
lnCF		0.00358*** (7.80E-05)		0.00334*** (0.000101)	0.0337*** (0.00161)
lnTEC			0.0184*** (0.000459)	0.0170*** (0.000514)	0.00861*** (0.00165)
lnCF×lnTEC					0.00176*** (9.81E-05)
GFCF	0.000672*** (0.000102)	0.000471*** (9.40E-05)	-0.00162*** (0.000132)	-0.00175*** (0.00015)	-0.00183*** (0.000153)
lnLA	0.512*** (0.00458)	0.482*** (-0.00787)	0.456*** (0.00596)	0.433*** (0.0063)	0.438*** (0.00648)
TO	0.0115*** (6.37E-05)	0.0115*** (0.000113)	0.0111*** (9.93E-05)	0.0112*** (0.000106)	0.0112*** (0.000112)
INDUS	0.0305*** (6.56E-05)	0.0306*** (0.000104)	0.0193*** (7.27E-05)	0.0193*** (7.23E-05)	0.0192*** (8.67E-05)
URBAN	0.0320*** (0.000201)	0.0300*** (0.000267)	0.0225*** (0.000225)	0.0211*** (0.0002)	0.0211*** (0.000192)
FDI	-0.00022 (0.000149)	-0.000211 (0.000142)	-0.000145 (0.000141)	-0.000156 (0.000141)	-0.000148 (0.000144)
INFLAG	-0.00106*** (1.53E-05)	-0.000977*** (1.46E-05)	-0.000479*** (1.33E-05)	-0.000380*** (1.18E-05)	-0.000379*** (1.18E-05)
Constant	-7.804*** (0.0703)	-7.350*** (0.125)	-6.354*** (0.0889)	-6.043*** (0.0923)	-6.553*** (0.107)
Observations	1,666	1,666	1,661	1,661	1,661
Groups	119	119	119	119	119
Instruments	114	115	115	116	117
VIF (mean/max)			1.78 / 2.81		
Hansen-J test[a] (p-value)	110.14 (0.297)	109.84 (0.304)	112.25 (0.251)	110.37 (0.292)	111.2 (0.273)
AR(1)[b] (p-value)	-1.7069 (0.0878)	-1.7089 (0.0875)	-1.9501 (0.0512)	-1.9476 (0.0515)	-1.9475 (0.0515)
AR(2)[b] (p-value)	0.2021 (0.8398)	0.1868 (0.8518)	0.1577 (0.8747)	0.1019 (0.9188)	0.1141 (0.9092)

*** p<0.01, **p<0.05, *p<0.1

Note: Standard errors are showed in brackets.

a: The Hansen-J test for overidentifying restrictions

b: The Arellano-Bond test for zero autocorrelation tionship depending on the conditions of the country, most previous studies have shown that renewable energy consumption has a positive effect on economic growth (Pao et al., 2015; Singh et al., 2019; Shahbaz et al., 2020; Mohsin et al., 2021). This explains that policies that promote renewable energy consumption at the macroeconomic level can drive economic growth as well as climate response (Inglesi-Lotz, 2016). Regarding the negative impact of carbon emissions, Abdollahi (2020) argued that most developing countries' manufacturing sectors are not as developed as those of developed countries, and consequently the carbon emissions actually harm productivity in terms of GDP. In addition, many empirical analyses have shown that carbon emissions lower economic growth in developing countries (Yanqing and Mingsheng, 2012; Omri, 2013; Maalej and Cabagnols, 2020; Sharif and Tauqir, 2021).

Climate finance and technology finance were found to have a positive impact on economic growth, which may be because the two types of finance are basically rooted in development finance that supports sustainable growth in developing countries (Steckel et al., 2017; Corsi et al., 2020; Abbasi et al., 2022; Bertheau and Lindner, 2022). In particular, technical assistance to developing countries can contribute to economic development as it serves as a driving force for the development of various types of infrastructure and industry (Kuroda et al., 2008; Gorelick and Walmsley, 2020). The cross term of climate finance and technology finance was been found to have a positive effect on economic growth. As the climate-resilient sustainable development trend is strengthened, climate finance and technology finance can mutually influence each other in terms of development cooperation and serve as a driving force for the economies of developing countries (Golombek and Hoel, 2011; Gu et al., 2022).

Meanwhile, among the control variables added to the economic equation, gross fixed capital formation, labor force, trade openness, industrialization, and urbanization showed a significant positive relationship, and the inflation factor showed a significant negative relationship, and these results can be confirmed in many previous studies (Marton and Hagert, 2017; Abdollahi, 2020). Gross fixed capital formation is essentially a key driver of economic growth in all countries, and it promotes economic growth through various effects such as creation of job opportunities, development of advanced technologies, increase of productivity, and expansion of industries, and the results of gross fixed capital formation can be interpreted from this point of view (Rahman et al., 2019).

Inflation rate was found to be a factor that hinders economic growth in developing countries, which also supports the results of most previous studies. However, depending on the analysis target, there are cases where the labor force and urbanization are not statistically significant, and in particular, the relationship of FDI with economic growth was not confirmed in the present study. However, since there are many reports that state that FDI is helpful, detailed country-by-country research is also required.

2. Results of estimation of energy equations

The energy equation estimation results for renewable energy consumption showed that both economic growth and carbon emissions in developing countries have a negative impact on renewable energy consumption, and these results are related to the EKC theory (Table 4). Most developing countries that receive financial climate and technical support are in their early stages of economic growth, and thus they tend to have low environmental sensitivity and focus only on industry and production. According to the EKC theory, this trend gradually worsens until a certain economic level is achieved (Shahbaz, 2021). Based on this, many empirical studies show that economic growth in developing countries reduces renewable energy consumption, while there are also arguments that the results vary across developing countries (Ahmed and Shimada, 2019; Prempeh, 2023; Athari, 2024). On the other hand, most studies on the negative impact of carbon emissions on renewable energy consumption have produced similar results (Pavlović et al., 2021; Ahmed et al., 2021; Zhang et al., 2022).

Meanwhile, in the analysis of the energy equation, climate finance exhibited a significantly negative influence on renewable energy consumption. Considering that climate finance includes climate change mitigation finance such as support for clean energy including renewable energy, there is need for further discussion. There are two possible reasons for this result. First, climate finance for developing countries may have been mainly invested in reducing greenhouse

Table 4. Results of the energy models

DV: REC	Model (1) [Basic]	Model (2) [lnCF]	Model (3) [lnTEC]	Model (4) [lnCF×lnTEC]	Model (5) [ALL]
L.REC	0.934*** (0.00342)	0.932*** (0.00325)	0.944*** (0.00363)	0.940*** (0.00316)	0.943*** (0.00317)
lnGDPP	-0.490*** (0.0266)	-0.498*** (0.0251)	-0.374*** (0.0191)	-0.377*** (0.0157)	-0.391*** (0.0161)
CO2	-1.551*** (0.058)	-1.558*** (0.0588)	-1.748*** (0.0634)	-1.759*** (0.0625)	-1.731*** (0.0651)
lnCF		-0.00590* (0.00318)		-0.0132*** (0.00369)	-0.362*** (0.0668)
lnTEC			0.448*** (0.0417)	0.445*** (0.0414)	0.146*** (0.0542)
lnCF×lnTEC					0.0206*** (0.00393)
GFCF	-0.0418*** (0.00303)	-0.0418*** (0.00303)	-0.0425*** (0.00266)	-0.0418*** (0.00267)	-0.0418*** (0.00265)
TO	0.00589*** (0.00116)	0.00608*** (0.00115)	0.00382*** (0.000792)	0.00390*** (0.000745)	0.00388*** (0.000852)
lnEC	0.886*** (0.0822)	0.895*** (0.0835)	1.627*** (0.0417)	1.640*** (0.0432)	1.611*** (0.0396)
INDUS	0.0483*** (0.00392)	0.0495*** (0.00367)	0.0527*** (0.00364)	0.0536*** (0.00327)	0.0552*** (0.00298)
URBAN	0.0421*** (0.00616)	0.0419*** (0.00626)	0.0449*** (0.00745)	0.0440*** (0.00752)	0.0435*** (0.0079)
FDI	0.00177 (0.00194)	0.00215 (0.0019)	0.000921 (0.00196)	0.00124 (0.0019)	0.00104 (0.00208)
lnPOP	-0.452*** (0.061)	-0.423*** (0.0629)	-0.886*** (0.0547)	-0.817*** (0.064)	-0.917*** (0.0636)
Constant	6.190*** (0.971)	5.862*** (1.018)	-2.135* (1.268)	-2.849** (1.295)	3.861*** (1.477)
Observations	1,764	1,764	1,756	1,756	1,756
Groups	126	126	126	126	126
Instruments	114	115	115	116	117
VIF (mean/max)			1.19 / 3.39		
Hansen-J test[a] (p-value)	113.57 (0.224)	113.57 (0.224)	113.59 (0.224)	113.55 (0.224)	113.55 (0.224)
AR(1)[b] (p-value)	-4.1938 (0.0000)	-4.1903 (0.0000)	-4.2211 (0.0000)	-4.2155 (0.0000)	-4.2123 (0.0000)
AR(2)[b] (p-value)	-0.1653 (0.8687)	-0.1656 (0.8684)	-0.1420 (0.8871)	-0.1323 (0.8948)	-0.1458 (0.8841)

*** p<0.01, **p<0.05, *p<0.1
Note: Standard errors are showed in brackets.
a: The Hansen-J test for overidentifying restrictions
b: The Arellano-Bond test for zero autocorrelation

gases from traditional energy sources rather than renewable energy, or the consistency of climate finance support may be lacking. Second, the effectiveness of energy policies in developing countries through climate finance may not be high. According to According to Shim (2023), climate finance other than the energy sector exhibited a negative impact on renewable energy generation, and climate finance on the energy sector also exhibited a minimal impact, and there results are similar to the results of the present study. In addition, according to an analysis by World Bank, renewable energy policies in developing countries through climate cooperation caused some adverse effects, suggesting that even though policies to promote the use of renewable energy were implemented, the proportion of renewable energy in the final energy mix decreased.[6] On the other hand, it was found that technology finance has a positive effect on renewable energy consumption, because the core strategy for activating renewable energy consumption is technology development, and previous studies also support this result (Athari, 2024). The cross term of climate finance and technology finance also confirms a positive relationship with renewable energy consumption. Climate cooperation can affect investment in the development of clean energy technology such as renewable energy in technology cooperation, which can contribute to encouraging the supply and consumption of renewable energy (Zhang et al., 2022).

Among the control variables added to the energy equation, gross fixed capital formation and population showed a negative relationship with renewable energy consumption, while trade openness, primary energy consumption, industrialization, and urbanization showed a positive effect. The relationship between gross fixed capital formation and renewable energy consumption can be predicted through the negative relationship between renewable energy consumption and economic growth. The results also differ depending on the on the analytical target, but studies such as Apergis and Payne (2012), Luqman et al. (2019), and Polycyn et al. (2021) support the results of the present study. The relationship between primary energy consumption and renewable energy consumption is similar to the results reported by previous studies (Polycyn et al., 2021). Although the proportion of fossil fuels in primary energy is high, the proportion of renewable energy has been gradually increasing since 2006, and thus an increase in primary energy consumption can lead to an increase of renewable energy consumption. Finally, the relationship of FDI with renewable energy consumption was not significant.

3. Results of estimation of climate equations

The climate equation estimation results showed that GDP per capita and GDP^2 per capita exhibited significant positive and negative relationships, respectively, supporting the EKC theory (Table 5). Although the validity of the EKC theory is still controversial, many studies have already confirmed that an inverted U-shaped pattern is derived (Hassan et al., 2020; Husnain et al., 2021). However, recently, many studies have been conducted to extend the traditional EKC hypothesis by further inputting $lnGDP^3$, and when statistically significant, an N-shaped or inverted N-shaped pattern is derived (Allard et al., 2018; Numan et al., 2022; Shouwu et al., 2024). The close relationship between renewable energy consumption and carbon emissions has also been emphasized in previous EKC-related studies. The analytical results of the present study confirmed that renewable energy consumption has a negative impact on carbon emissions, which is similar to most previous studies (Dong et al., 2017; Akram et al., 2020; Brini, 2021; Huang et al., 2021; Zhang et al., 2022). Furthermore, many studies have been conducted on the Renewable energy Kuznets Curve (RKC), which estimates the time-series relationship between renewable energy and income. An RKC study also showed that renewable energy can not only contribute to reducing carbon emissions but also bring forward the income threshold earlier than the EKC (Yao et al., 2019; Naqvi et al., 2021).

Meanwhile, climate finance and technology finance showed an opposite relationship with carbon emissions. When examined in conjunction with the results of the energy equation, it is presumed that climate finance is still being used to limit traditional energy sources centered on fossil fuels rather than to promote renewable energy consumption (Sim, 2023; Lee et al., 2020). Technology finance is invested in not only climate technology or green technology such as renewable energy, but also for various advanced technologies with the goal of improving the overall technological level and capacity of developing countries (Dodgson, 2018; Shahsavari and Akbari, 2018; Eriksen et al., 2021). Above all, since the fundamental nature of technology finance is development finance, carbon emissions may increase when it is invested in the development of infrastructure and industry in developing countries. Studies have shown similar cases where supporting technological innovation or technology-related R&D can actually lower environmental quality by increasing carbon emissions in developing countries (Newell and Henderson, 2011; Kivyiro and Arminen, 2014; Pan et al., 2019; Acheampong et al., 2020; Chen and Lee, 2020). On the other hand, it was confirmed that the interaction term between climate finance and tech-

Table 5. Results of the climate models

DV: CO2	Model (1) [Basic]	Model (2) [lnCF]	Model (3) [lnTEC]	Model (4) [lnCF×lnTEC]	Model (5) [ALL]
L.CO2	0.718*** (0.00123)	0.715*** (0.00126)	0.652*** (0.00135)	0.648*** (0.00151)	0.648*** (0.0013)
lnGDPP	0.0717*** (0.000969)	0.0763*** (0.00101)	0.0662*** (0.00163)	0.0711*** (0.00175)	0.0724*** (0.00184)
lnGDPP2	-0.630*** (0.0123)	-0.657*** (0.0137)	-0.516*** (0.026)	-0.545*** (0.0266)	-0.549*** (0.0282)
REC	-0.0269*** (0.000273)	-0.0268*** (0.000282)	-0.0272*** (0.000364)	-0.0272*** (0.000317)	-0.0272*** (0.000342)
lnCF		-0.00577*** (0.000221)		-0.00637*** (0.000193)	-0.00740*** (0.000351)
lnTEC			0.0939*** (0.0013)	0.0921*** (0.00111)	0.164*** (0.00327)
lnCF×lnTEC					-0.00476*** (0.000209)
GFCF	4.75E-05 (9.69E-05)	0.000123 (0.000108)	-9.49E-05 (7.38E-05)	2.91E-05 (9.24E-05)	-7.40E-05 (8.63E-05)
TO	0.00195*** (4.76E-05)	0.00181*** (4.90E-05)	0.00130*** (4.60E-05)	0.00117*** (5.16E-05)	0.00112*** (5.55E-05)
lnEC	0.164*** (0.00614)	0.164*** (0.00633)	0.353*** (0.00811)	0.352*** (0.00913)	0.349*** (0.00716)
INDUS	0.0132*** (7.71E-05)	0.0124*** (7.45E-05)	0.0147*** (0.000108)	0.0137*** (0.000105)	0.0135*** (0.000115)
URBAN	0.0354*** (0.000356)	0.0395*** (0.000368)	0.0412*** (0.000392)	0.0415*** (0.000422)	0.0334*** (0.000396)
FDI	-0.000231 (0.000148)	-0.000147 (0.000133)	-0.000144 (0.000182)	-0.000112 (0.000187)	-0.000152 (0.000139)
Constant	0.713*** (0.0683)	0.768*** (0.0783)	-3.002*** (0.117)	-2.896*** (0.134)	-4.090*** (0.156)
Observations	1,764	1,764	1,756	1,756	1,756
Groups	126	126	126	126	126
Instruments	114	115	115	116	117
VIF (mean/max)			1.55 / 2.17		
Hansen-J test[a] (p-value)	108.83 (0.328)	107.82 (0.353)	108.92 90.326)	106.14 (0.396)	108.03 (0.348)
AR(1)[b] (p-value)	-2.5125 (0.012)	-2.5496 (0.0108)	-2.4839 (0.013)	-2.5249 (0.0116)	-2.531 (0.0114)
AR(2)[b] (p-value)	0.9147 (0.3604)	0.9687 (0.3327)	0.7516 (0.4523)	0.8014 (0.4229)	0.7156 (0.4743)

*** p<0.01, **p<0.05, *p<0.1
Note: Standard errors are showed in brackets.
a: The Hansen-J test for overidentifying restrictions
b: The Arellano-Bond test for zero autocorrelation

nology finance reduces carbon emissions. When climate finance is invested in climate technology in relation to climate change mitigation, it can ultimately cause technology finance to be provided to promote technological development and improve technological levels, which is interpreted as having a positive impact on reducing carbon emissions (Rio, 2009; Haque and Rashid, 2023).

Among the control variables added in relation to the climate equation, trade openness, primary energy consumption, industrialization, and urbanization were found to have a positive impact on carbon emissions. In particular, when companies of developed countries under strict climate regulations relocate their factories to developing countries where the regulations are loose, the trade openness of developing countries may be considered positively. For this reason, the results on trade openness support the so-called 'pollution haven' hypothesis, which states that trade openness increases not only economic growth but also carbon emissions in developing countries (Rana and Sharma, 2019; Gill et al., 2018). Primary energy consumption was found to have a positive effect on renewable energy consumption, but in reality, the proportion of fossil fuels is much higher, and thus an increase in carbon emissions is unavoidable (Lee et al., 2020). Meanwhile, the absence of a significant impact of gross fixed capital formation and FDI on carbon emissions was confirmed.

V. Conclusions and Implications

In the present study, an analysis of the economy-energy-climate nexus was conducted with 126 developing countries in order to examine the interrelationships among economic growth, renewable energy consumption, and carbon emissions in developing countries due to the exacerbation of climate change. The analytical results confirmed that all three factors have bidirectional causality, except for the difference between positive and negative effects (Table 6). Renewable energy consumption can promote economic growth, while carbon emissions can serve as a factor that reduces economic growth. Economic growth and carbon emissions have a negative effect on renewable energy consumption, while renewable energy consumption can help reduce carbon emissions, confirming the EKC hypothesis for carbon emissions.

Table 6. Summary of main results

Variable	Economy model	Energy model	Climate model
GDP per capita	-	negative	positive negative
Renewable energy consumption	positive	-	negative
CO_2 emissions	negative	negative	-
Climate-related development finance	positive	negative	negative
Technical cooperation grants	positive	positive	positive
Interaction term of climate & technology	positive	positive	negative

Meanwhile, in order to differentiate this work from previous studies, the present study investigated the influence of climate cooperation and technology cooperation on the economy-energy-climate nexus. Climate cooperation and technology cooperation have emerged as key strategies for responding to climate change, and the international community is looking forward to seeing their synergistic effect, especially in terms of climate change mitigation. In previous studies that analyze developed countries, green bonds and technological innovation indexes are usually input as main explanatory variables using a combination of green finance and green technology or technological innovation. However, since the present study was conducted with developing countries as subjects, climate finance and technological cooperation finance, which are rooted in development finance, were used as proxy variables for climate cooperation and technological cooperation.

The analytical results showed that both climate finance and technology finance had a significant positive relationship with economic growth, and the cross-term of climate finance and technology finance also had a positive influence. This is reasonable in the sense that both types of finance are part of development finance that promotes growth in developing countries. Next, climate finance exhibited a negative influence on renewable energy consumption, and this can be interpreted as a tendency of climate finance to be focused more on reducing consumption of other fossil fuel-based energy than on developing renewable energy, and that policies related to renewable energy are somewhat inconsistent. It was found that technology finance has a positive impact on renewable energy consumption, which can be understood from the viewpoint that renewable energy is a typically technology-based energy source. The cross term of the two types of finance was found to be able to contribute to renewable energy consumption, suggesting that technology cooperation finance invested in clean energy development has increased as the importance of climate technology is emphasized in climate cooperation. Finally, climate finance showed a negative relationship with carbon emissions, while technology finance showed a positive relationship, indicating that climate finance can contribute to reducing carbon emissions, while technology finance can increase carbon emissions. Considering that climate finance was invested only for the purpose of climate change mitigation in 2002 when the Rio marker was introduced, this result confirms the effectiveness of climate finance. Technology finance supports all technological developments to support the development and growth of developing countries, including climate technology. The result thus shows that technology finance is closely related to the promotion of urban and infrastructure development, industrialization, and the like. The cross term of climate finance and technology finance confirms the effect of reducing carbon emissions, which is also inferred to be the result of the same interactive influence as renewable energy consumption.

Through the above-described analytical results, we herein suggest two policy implications. First, it is necessary to improve financial policies more strategically and in a more balanced manner in consideration of the synergistic effects of climate cooperation and technology cooperation for developing countries. Climate finance is still exhibiting low effectiveness and systemicity in renewable energy support policies, and it is believed that improvements can be made through technology cooperation. Second, rapid climate mainstreaming work is required in technology cooperation. Since technology plays a core role in responding to climate change, climate cooperation should be promoted focusing on the development of green technology and climate technology aimed at responding to climate change in order to build a society that can enable low-carbon and carbon-free energy utilization. In particular, considering the analytical results that the influence of technology cooperation subsidies on the economy, energy, and climate is significant, a stage of advancing technology cooperation with developing countries should be prepared in the future. The present study has derived meaningful policy implications by identifying the connectivity between economy-energy-climate in developing countries and analyzing the impact of climate cooperation and technological cooperation, but has limitations in that the results may differ by country due to the complex causal relationships between economy, energy, and climate (Polcyn et al., 2021). Therefore, further studies may need to be conducted to expand the research by considering the homogeneity of countries.

Note 1. Indonesia, which has recently experienced rapid economic growth and has the world's fourth largest population, has become the first ASEAN country to officially join BRICS as the 10th member.

Note 2. In this paper, climate cooperation and technological cooperation refer to development cooperation in the climate and technological fields between developed and developing countries, and climate-related development finance and technical cooperation grants refer to financial support for climate cooperation and technological cooperation, respectively.

Note 3. (Article 4, Paragraph 1) ...All Parties shall promote and cooperate in the transfer, development, application and diffusion of technologies for regulating, reducing and preventing anthropogenic emissions of greenhouse gases. (Article 4, Paragraph 5) Developed country Parties ... shall take all practicable measures to promote the transfer of environmentally friendly technologies and know-how to developing countries.

Note 4. It uses the moment condition that the covariance between the instrumental variable and the error term is zero.

Note 5. The test results are provided in the panel analysis result table.

Note 6. 'Is the Gap Widening? Assessing the Current Renewable Energy Policies in Developing Countries' (World Bank Blogs, June 1, 2023).

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